CLEANER
Clean Heat and Power from Hydrogen

CLEAN HEAT AND POWER FROM HYDROGEN

Grant agreement no.: 101137799
Start date: 01.01.2024 – **Duration**: 48 months.
Project Coordinator: Anders Ødegård, SINTEF

DELIVERABLE REPORT

D2.1 TEST BENCH VALIDATION REPORT	
Due Date	Month 15
Author (s)	Johannes Lehmuskoski, Jari Ihonen, Lius Daniel (VTT)
Work package	WP2 System testing
Work package Leader	Johannes Lehmuskoski
Lead Beneficiary	VTT
Date released by WP leader	27.06.2025
Date released by Coordinator	14.07.2025

DISSEMINATION LEVEL		
PU	*Public*	*X*
SEN	*Sensitive, limited under the conditions of the Grant Agreement;*	
NATURE OF THE DELIVERABLE		
R	*Document, report*	*X*
DEM	*Prototype demonstrator*	
DEC	*Website*	
DMP	*Data management plan*	
OTHER	*Software, algorithms, models*	

SUMMARY	
Keywords	*PEMFC system testing, climate container, test bench*
Abstract	*CLEANER project examines the use of industrial grade hydrogen as a fuel in PEM hydrogen fuel cells. The cost of hydrogen can be reduced, if the purity requirements can be alleviated. VTT Climate container has been selected to function as a platform for testing the impurity tolerant fuel cell systems developed in the project. The test bench operation was tested and validated in Task 2.1 and the results are reported here. The test bench was updated with additional cooling capacity, impurity supply to the fuel line, and Micro GC to monitor exhaust gases. The test bench was tested by running a 25-kW fuel cell system in it. All the tested subsystems proved to reach presumed operability and allow running a 100-kW fuel cell system in the test bench. The impurity mixing to the fuel line was tested without fuel supply. The impurity feed controllability was precise and changing of flow conditions had no effect on it.*

REVISIONS			
Version	**Date**	**Changed by**	**Comments**
0.9	28.05.2025	Johannes Lehmuskoski	Draft
1.0	11.06.2025	Johannes Lehmuskoski	Shared with partners for review
1.1	27.06.2025	Johannes Lehmuskoski	Published by WP leader after review
1.2	09.07.2025	Johannes Lehmuskoski	Updated information on MFCs

The CLEANER project is supported by the Clean Hydrogen Partnership and its members. The project is co-funded by the Research Council of Norway and the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee.

D2.1 TEST BENCH VALIDATION REPORT

CONTENTS

1. INTRODUCTION

Testing of fuel cell system operation with industrial grade hydrogen is the core of the work package 2 (WP2), and a key element for the CLEANER – Clean Heat and Power from Hydrogen project [1]. In the project work package 1, fuel cell systems are modified to withstand most relevant impurities in industrial grade hydrogen. In the first task of WP2, Climate Container at VTT is modified to accommodate and test the impurity tolerant fuel cell systems of 100-kW output power. The modified Climate container is used to simulate operation of a fuel cell system with industrial grade hydrogen fuel source. Another fuel cell test system build in Maranda project[2] has also been tentatively prepared to function as a back-up test platform for WP2.

Climate container operation was validated by operating Powercell MS30; a 25-kW fuel cell system from Powercell in the test bed. The main features of the test bed regarding the impurity tolerance testing are: impurity feed to the fuel supply, gas analysis of the fuel cell exhaust gas, and feed of air to fuel cell air bleed input. In MS30 fuel cell system, possibility for air bleed input does not exist, so this feature is not reported here, but only later with the 1st generation impurity tolerant 100 kW Powercell system.

The MS30 fuel cell system has lower output power than the fuel cell systems developed in the CLEANER project. Thus, the operation of the test bed at maximum test power was not tested. However, test bed functionality was tested at maximum power of MS30 fuel cell system, and based on the test results and system specifications the operability with 100-kW system was assessed.

The impurity feed lines were tested by mixing two impurity gas supply lines together and combining them to the fuel supply line. The control and mixing of the impurity gases was tested and is reported here.

Gas composition of anode exhaust gases from the developed impurity tolerant fuel cell systems will be monitored with a micro gas chromatograph (Micro GC). The Micro GC was tested by measuring output from the exhaust line of the MS30 fuel cell system, which is a mix of anode and cathode exhaust.

Herein, we report the main features and modifications of the Climate container fuel cell system test bed, and validation of the test bed operation for fuel cell system impurity tolerance testing.

2. Test bench features

2.1 Existing features

The Climate container that functions as the system test bed is based on a containerised AVL e-Storage Emulator/Tester 320 kW commissioned at VTT in 2012. The tester is controlled by Lynx software installed on a standalone PC combined with control and data acquisition hardware. In total there are over 80 configurable I/O ports for analogue and digital channels. In addition, CAN bus is available for communication with systems and components under test. The container is thus very flexible for testing different battery and fuel cell systems.

The tester power electronics include power distribution unit (PDU), power distribution switch box (PDSB), and DC power source/sink. The power electronics allow sinking and sourcing maximum of 320 kW electric power. The maximum current is ±600 A, and voltage ±1000 V. The PDU and PDSB contain automated safety features to limit overvoltage and -current, and to safely switch-off power in error situations.

The Climate container has automatic temperature control of the test space realised with heaters and coolers. The temperature settings are controlled in Lynx or in the Climate container remote control panel. The container test space temperature can be cooled below -30 °C for cold testing, or heated up to 40 °C.

Gas lines for hydrogen and nitrogen supply are installed for the container. The hydrogen supply pressure of approximately 40 barg is adjusted with two Swagelok pressure regulators to 2 – 14 barg range. The regulators allow high hydrogen flow of over 2500 slpm. Nitrogen supply has line pressure of 10 barg. The nitrogen line is used for inertising of the container test space by replacing air in the container with nitrogen. The lower limit of explosion of hydrogen is 4 % of oxygen, thus the container is maintained below 4 % oxygen concentration during fuel cell testing. Nitrogen is available also for other uses via a T-junction.

Gas safety in the container is monitored with Crowcon Gasmaster and four gas sensors, two for oxygen and two for hydrogen. Alarm limit for hydrogen in the container during testing is 20 % of the lower explosive limit. The hydrogen alarm is configured in a hardwire safety loop to disconnect all electricity from the container and disconnect the DC linkage. Oxygen is monitored with a Crowcon Xgard Bright oxygen sensor and a SICK Transic100LP laser oxygen transmitter. Via Lynx, oxygen monitoring prevents supplying hydrogen to the container if oxygen concentration is above 4 %. In addition, an oxygen concentration below 10 % illuminates a notification light indicating unsafe oxygen level for human in the container.

Safety systems of the Climate container include pressure and temperature monitoring. The gas input lines are equipped with pressure and temperature transmitters. The container test space temperature is monitored as well as the air intake and exhaust temperatures. Exceeding safe temperature or pressure limit triggers emergency stop of the test system.

Type of emergency stop depends on the safety limit exceeded. The most severe limit violations result in immediate switching-off of power to the container, while less severe triggers a controlled shutdown sequence of a system under test. Other safety features are for example door opening and closing detection of the test space. Test run cannot be started or a test run stops, if the test space doors are opened.

2.2 Climate container update

The Climate container was modified to meet the Powercell 1st generation impurity tolerant fuel cell system requirements listed in Table 1. The modifications included installing two cooling systems: one for a fuel cell stack and another for fuel cell system balance of plant (BoP) components. The BoP cooling cools mainly the fuel cell air compressor that delivers air to the cathode. All the systems presented here were connected to the Powercell MS30 system to validate their functionality. The P&I diagram of the Climate container with Powercell fuel cell system is presented in Appendix 1.

Air to the fuel cell system cathode is taken from the ambient air around the container through an air duct, which is equipped with Freudenberg FC F-0513-N air filter. Before the test with the 1st generation fuel cell system, the Freudenberg air filter will be replaced with Entaron FC 13 airfilter from MANN+HUMMEL that allows sufficient airflow for the 100-kW fuel cell system.

For impurity testing, gas lines for controlled impurity mixing with the hydrogen fuel supply were installed. The impurity lines allow mixing of two impurities that are diluted with nitrogen or hydrogen simultaneously.

Gas analysis to monitor fuel cell exhaust gas composition was carried out with a Micro-GC. In the 100-kW Powercell fuel cell system, gas analysis is to be done only from anode exhaust gases. In the Powercell MS30 system, the cathode and anode exhaust lines are combined before they exit the fuel cell system, so it was not possible to monitor anode exhaust gas separately and the measurement was done from the mixed exhaust gas.

Table 1. Specifications of the 1st generation impurity tolerant fuel cell system

Subsystem	Property	Min	Max	Unit
Electric output				
	Power	0	129	kW
	Voltage	215	390 (peak 455)	VDC
	Current	45	450	A
Electric input		(nominal)		
Low voltage input	Power	(75)	240	W
	Voltage	(24)	24	VDC
	Current	(3)	10	A
High voltage input				
	Power	0	25	kW

	Voltage	500	750	VDC
	Current	33	50	A
Anode				
	H2 supply pressure	3	8	barg
	H2 supply temperature	5	70	°C
Cathode				
	Cathode inlet pressure	ambient		
	Input humidity RH	10	95 (non-condensing)	%
Cooling				
Fuel cell cooling	Coolant type	Glysantin		
	External HEX cooling capacity	15	150	kW
Component cooling	Coolant type	Glycol/DI-water		

2.2.1 Cooling systems

Stack cooling system (high-power cooling, HPC), and component cooling system (low-power cooling, LPC) were assembled as two separate entities. A photo of the installations outside the container is shown in Figure 1.

Figure 1. Coolant loop installations outside the container before addition of heaters and insulation. In the lower left corner, the Iwaki coolant pump is connected via piping to 3-way valve and Alfa Laval plate heat exchanger. The tubes going over the heat exchanger are connected to the fuel cell system inside the container. The black tubes the most left are the tubes connected to the Hydac cooler. On the right is the Ecocoil cooler for the component cooling loop.

2.2.1.1 Stack cooling system

The HPC cooling the fuel cell stack under examination, consists of two coolant loops: primary and secondary. The primary coolant loop connects directly to the fuel cell system and the secondary coolant loop cools the primary coolant via a heat exchanger. The schema of the HPC system is presented in Figure 2.

Alfa Laval plate heat-exchanger AlfaNova 76-60H is used to transfer the heat between the two coolant loops. The heat exchanger is positioned outside the Climate container and the secondary coolant loop is assembled completely outside the container.

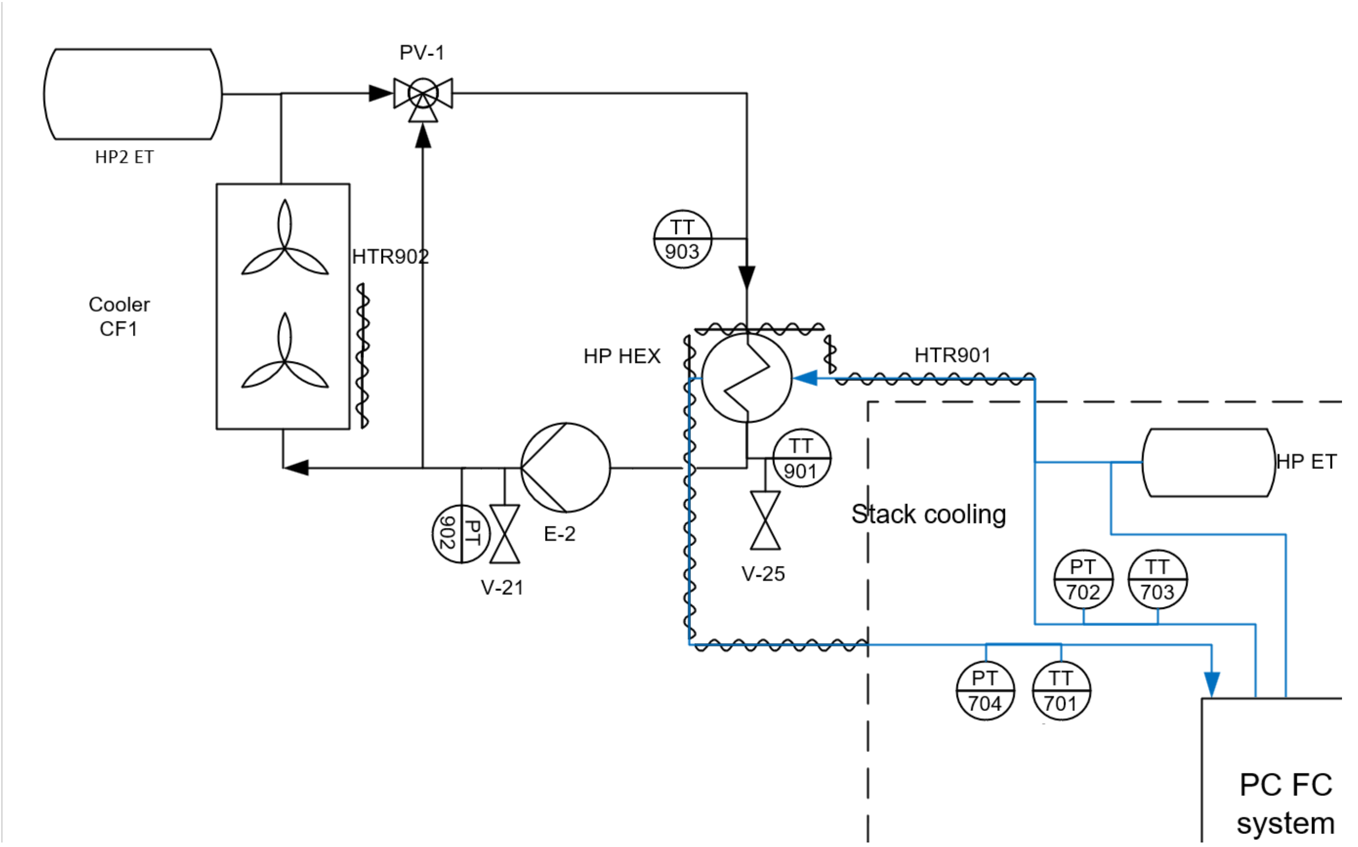

Figure 2. P&I diagram of the stack cooling system. The primary coolant line is coloured blue, and the secondary coolant line is in black. Iwaki pump is denoted as E-2 and the Alpha Laval heat exchanger as HP HEX. HP ET and HP2 ET are the expansion tanks of the primary and secondary loops, respectively. HTR901 and HTR902 are the heaters positioned on primary coolant line and inside Hydac cooler, respectively.

Most of the primary coolant loop is inside the container, with only a small section connecting to the heat exchanger inlet and outlet located outside. The heat exchanger and the primary coolant line section outside were wrapped with line heater and insulated with foam rubber. The line heater can be used when tests are started in winter when ambient temperature is below zero. Preheating the primary coolant prevents sub-zero temperature coolant entering the fuel cell system, and formation of freezing conditions inside the fuel cell stack.

The primary coolant line connects directly to the fuel cell system coolant inlet and outlet. In addition, the outlet line is connected to an expansion tank. In Powercell MS30 system a fuel cell cooling vent line is also required to be connected to the expansion tank, and this was included to the primary line.

The primary line is equipped with pressure sensors and temperature transmitters at fuel cell coolant inlet and outlet. The primary coolant flow is driven by a pump in a fuel cell system under tests.

The secondary coolant has temperature sensors before and after the heat exchanger. After heat exchanger, Iwaki MX-401 pump with maximum capacity of 150 lpm pumps the coolant through a T-connection to Hydac AC-LN12S cooler and a three-way servo-controlled proportional valve.

The three-way valve controls the portion of coolant going through the cooler. In the default setting of the valve, all coolant flows through the cooler. In the opposite setting, all coolant is circulated directly back to the heat exchanger. The valve setting is adjustable over a continuous range. This way the system cooling power can be adjusted, when the two cooler fans are set to run at constant speed.

The cooler is rated to approximately 140 kW cooling power at 150 lpm water/glycol flow and 30 °C temperature difference between coolant inlet and intake air. The cooler has two fans with maximum rotation speed of 1500 rpm producing total maximum air flow of 33 000 m^3/h. The fans are run by Danfoss FC-302 inverter drives that have option for CAN bus control.

The secondary coolant loop is equipped at the Hydac cooler with a 2000 W resistor heater. The heater can preheat the secondary coolant close to °0 C before starting the fans, if the system needs to start at very low ambient temperatures. The preheating prevents heavy temperature gradients and allows faster warm-up to operating temperature in system startups

A pressure sensor after Iwaki pump monitors the pump functioning. The secondary coolant loop includes an expansion tank above the cooler.

2.2.1.2 BoP cooling system

The LPC cools the fuel cell BoP and is connected directly to the fuel cell system component coolant inlet and outlet. Coolant temperature and pressure are monitored at fuel cell system inlet and outlet with temperature sensors and pressure transmitters.

An EMP W29 pump is used to recirculate the coolant. The pump is located upstream of the fuel cell system inlet and an expansion tank is connected to the line upstream of the pump.

Ekocoil ECHL-drycooler 450 is set outside the container and the coolant inlet and outlet lines were connected to it via inlets through container wall. The cooler is rated to 12.3 kW cooling power at 30 °C intake air and 60 lpm 50 % water/ethylene glycol flow with incoming fluid temperature at 50 °C.

The part of the line outside the container going to the cooler was entwined with line heater and wrapped with insulator. Again, this was done to prevent sub-zero temperature coolant from reaching the fuel cell system and speedup warm-up to operating temperature during system startups in winter.

2.2.2 Impurity gas feeds

Two gas lines were prepared to allow feeding of two separate impurity gas mixtures simultaneously. The two lines mix before connecting with hydrogen supply line. 50-litre gas cylinders or cylinder bundles at 200 bar can be connected as impurity gas reservoirs for the lines. The P&I diagram is shown in Figure 3.

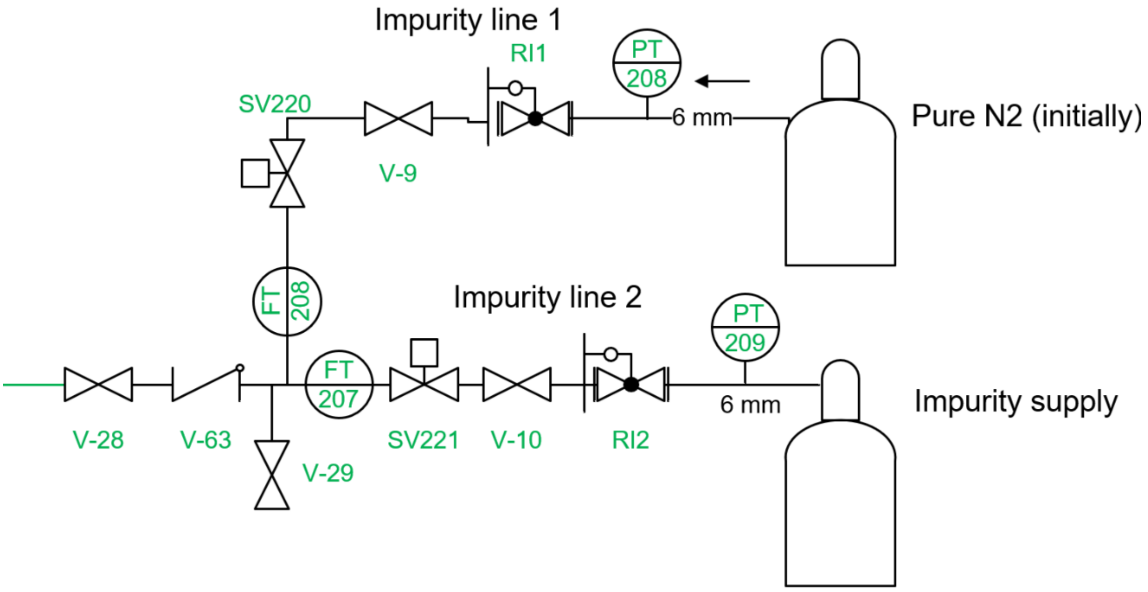

Figure 3. Impurity feed lines. The connection to the fuel line is to the left from V-28.

The gas reservoir pressures are monitored with pressure transmitters before the pressure is reduced to 20 bar with a Swagelok KCY-type pressure regulators.

6 mm diameter impurity feed lines connect via solenoid valves to Bronkhorst IN-FLOW Select mass flow controllers (MFC). Impurity line 1 has model F-112 MFC with control range of 2.4…120 slpm with nitrogen. Impurity line 2 has model F-201 MFC with control range of 1.2…60 slpm with nitrogen.

The impurity lines are combined before they connect to the fuel line after a check valve. Manual valves are positioned between the mixing of fuel and impurity lines and on the impurity lines.

Impurities, such as carbon monoxide, mixed with either hydrogen or nitrogen can be used as the impurity supply gases. The mixing ratios are selected to ensure appropriate impurity concentrations for testing the fuel cell system.

Initially, pure nitrogen, and 1000 ppm CO in nitrogen were selected for the impurity gases 1 and 2, respectively. The pure nitrogen is used for reaching the project target of 5 % impurity concentration in the fuel supply. At 100 kW fuel cell output power and 1125 slpm fuel consumption (assuming 50 % system energy conversion efficiency and using hydrogen lower heating value), 5 % nitrogen concentration is achieved with 60 slpm nitrogen flow.

The maximum rated flow of MFC in impurity line 2 is 60 slpm, so the maximum CO concentration from a 1000 ppm impurity mixture at 100 kW system output is 51 ppm. The lowest CO concentration at this output power with the MFC is 1.1 ppm. Nitrogen and carbon monoxide concentrations of different impurity gases mixed with hydrogen supply are shown in Table 2. If the fuel cell output power is decreased to 50 kW, the nitrogen and impurity concentrations are doubled, if the impurity gas flows are kept unchanged.

Nitrogen can be replaced with hydrogen in the impurity gases to get a CO mixture with pure hydrogen in the fuel supply. The CO can be replaced also with different impurities.

Table 2. Possible impurity concentrations.

	Fuel cell output power:	100 kW		50 kW	
	Hydrogen supply flow:	1125 slpm of H2		562 slpm of H2	
Impurity gas composition:	Impurity feed flow:	N2 concentration in H2	CO concentration in H2	N2 concentration in H2	CO concentration in H2
1 % CO in N2	1.2 slpm	1060 ppm	11 ppm	2110 ppm	21 ppm
	60 slpm	5.0 %	510 ppm	9.5 %	960 ppm
1000 ppm CO in N2	1.2 slpm	1060 ppm	1.1 ppm	2130 ppm	2.1 ppm
	60 slpm	5.1 %	51 ppm	9.6 %	96 ppm
100 ppm CO in N2	1.2 slpm	1070 ppm	0.11ppm	2130 ppm	0.21 ppm
	60 slpm	5.1 %	5.1 ppm	9.6 %	9.6 ppm

2.2.3 Micro GC

The Agilent 990 Micro GC gas chromatograph is employed to monitor the composition of fuel cell exhaust gas. In the first-generation fuel cell system, samples are taken from the anode exhaust gas via a buffer tank for purge gas. Sampling on the cathode is also possible. In the Powercell MS30 system, samples are taken from the system exhaust line, which is a mix of exhausts from both anode and cathode outlets. Thus, monitoring of only from anode outlet gas at this stage cannot be demonstrated, but it will be made available for Task 2.2.

Helium is utilized as the carrier gas for the gas chromatograph because it does not limit oxygen detectability as argon does. However, helium impacts the Micro GC's ability to measure hydrogen, especially at low concentrations.

The accumulation of argon in the anode loop can make measurement of low levels of oxygen difficult, as shown in previous MetroHyve2 project [3]. However, in the measurements of CLEANER project, high level of N2 is expected in H2 fuel, which requires relatively frequent purge and low fuel utilisation. This would limit argon enrichment in anode loop so that both Ar and O2 could be measured.

The Micro GC used in this project incorporates two columns: molecular sieve and Poraplot. Molecular sieve is a solid adsorbent with a high porosity structure, suitable for permanent gases (O_2, N_2, CH_4, CO). It can absorb moisture easily; hence, the sample needs to be dry, particularly during long-term monitoring. Poraplot columns typically use organic or inorganic sorbents, allowing effective separation of low molecular weight hydrocarbons (CO_2, C_xH_y). Examples of sorbents for Poraplot include silica and alumina. The order of peak appearance in each column remains consistent, however, the retention time of each element's peak varies depending on injection and column conditions. The interval between each injection is determined by users but is typically limited by the retention time required to measure the targeted gas. The retention time for each element depends on measurement parameters such as column temperature and injection temperature. For this measurement, an interval of 2 minutes was selected as it is sufficient to capture CO peaks, which have the longest retention time. Table 3 summarizes the typical retention time and detection limit applicable to this campaign. If O_2 and Ar are both needed to be measured, then different parameters should be used, meaning lower column temperature for molecular sieve column.

Table 3. Details of gas measurement by Agilent 990 used in this project

Gas	Column	Retention time (min)	Detection limit (ppm)
Oxygen & Argon	Molecular sieve	0.38 - 0.40	5
Nitrogen	Molecular sieve	0.42 - 0.48	5
Carbon monoxide	Molecular sieve	0.82 - 0.84	5
Carbon dioxide	Poraplot	0.33 - 0.35	5

The Micro GC and apparatus setup are shown in Figure 4. A Nafion tube dryer is used with 500 mL/min nitrogen as a drying gas in the counter flow, since the molecular sieve column cannot tolerate moisture for extended periods, even when RTS and backflush are applied. The sample line is equipped with a pressure reducer to lower the pressure to less than 50 mbarg and a rotameter to further reduce the sample flow rate to less than 100 mL/min. This setup ensures continuous injection of samples into the Micro GC.

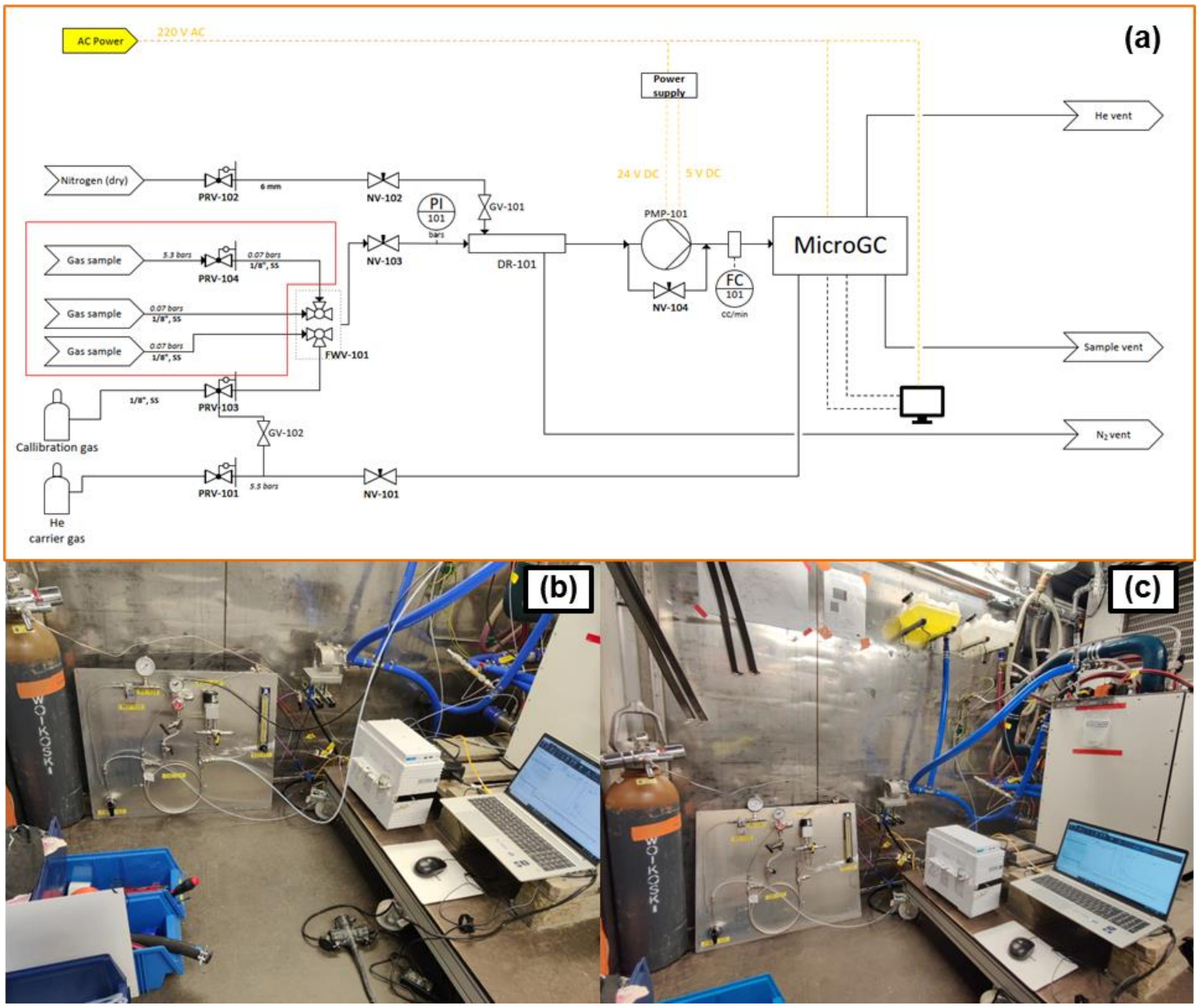

Figure 4. (a) P&ID, (b) and (c) photos of the Micro GC setup for gas measurement in a fuel cell container

3. Validation

Operation of the Climate container test station was validated by operating Powercell MS30 fuel cell system in it and measuring gas exhaust composition with Micro GC. Operation of impurity gas lines was tested separately without running the fuel cell system or supplying hydrogen.

3.1 System tests

3.1.1 Climate Container safety and inertisation

Operation of a fuel cell system in the Climate Container requires significant amount of hydrogen, and therefore carefully designed safety features. In the core of hydrogen safety of the Climate Container is the inertisation of the container test space. Nitrogen is the inertising medium in the Climate Container.

Nitrogen inertisation of the container was tested before operating the fuel cell system. The system automation programmed on Lynx contains an automated control for the inertisation. The automation requires a manual confirmation that the container doors are closed, and simultaneously it is confirmed that no-one is inside the container. After pushing of a confirmation button next to the container, the inertisation is allowed to start.

The inertisation procedure took about 15 – 20 minutes to dilute from atmospheric air composition to below 4 % oxygen concentration, which prevents hydrogen ignition at any hydrogen concentration. During this time, the nitrogen input proportional valve was 100 % open and a calculated nitrogen flow is 1200 slpm.

A fan inside container is used to circulate air inside the container, while the inertisation is ongoing. The fan ensures complete mixing of gases. Also, all feed throughs to the container are blocked, except for a small conduit that allows air to exit the container.

After below 4 % oxygen concentration is reached, the nitrogen inlet valve is set automatically to 8 % opening. This enables a 100 slpm nitrogen flow to the container that maintains sufficiently low oxygen concentration. During the tests it was realised that even lower nitrogen flow can be sufficient, if the leak tightness of the container is ensured.

The inertisation and its permanence is always tested when a new system is installed in the container, or connections out from the container are changed.

Once the inertisation of the container was confirmed, hydrogen supply valve had a permission to open and system tests with Powercell MS30 fuel cell system could be started.

3.1.2 Operating a fuel cell system in the container

Climate container testing is controlled by Lynx software on a PC in a monitoring room situated nearby the container. The PC is connected to the AVL PLC via ethernet cable. Datalogging is done on the PC.

Cooling systems are started before sending a startup command to the fuel cell system. In the system tests, the cooling pumps for both stack cooling and component cooling were started, and the cooler fans were set to half of the maximum control speed.

Elektro-Automatik ELR 10500-90 at 500 V was used as a power supply for the high voltage input of the Powercell MS30. Delta Elektronia SM66-AR-110 was used to provide power to a 24 VDC input of the fuel cell system.

Once power is supplied to the Powercell MS30, it starts communicating via CAN-bus. Most important information sent by the fuel cell system are the fuel cell system state, current request, output power and error messages. CAN bus messages sent to the Powercell MS30 are the power request, state request and error reset messages. Once error messages can be cleared and fuel cell status is ‘Standby’, the fuel cell system is ready to start.

When testing Powercell MS30 fuel cell system, the PDU unit in the AVL tester was operated in current-following mode. The Powercell MS30 is controlled by setting a power request in kilowatts.

When MS30 receives a power request from Lynx software via CAN-bus, it sends back a current request. The current request is then passed in Lynx to AVL PDU, which draws the current requested from the fuel cell system. The voltage sets to a level the fuel cell system can maintain, while producing the requested output current.

A startup is initiated in Lynx where status request for the fuel cell system is switched from ‘Standby’ to ‘Run’. The Powercell MS30 moves to ‘Startup’ state, goes through its automatic startup procedures, and starts consuming hydrogen and generating electricity. When the startup procedure is finished, the system state changes to ‘Running’, and the fuel cell system produces a default output power of 4.2 kW. The output voltage was 210 V and current 20 A.

The system was ramped up in steps up to power request of 23 kW. At 23 kW power request, the system could not run stable, possibly because of long storage before use. At 22 kW power request, the operation was stable, and the total output power was 24.8 kW. From the total output power, the power consumption of the fuel cell system’s BoP is not subtracted.

Hydrogen pressure in the supply line at pressure transmitter PT204 before connection to fuel cell system fell by 0.32 bar from 8.77 barg to 8.45 barg at 22 kW power request, when operating with single Swagelok RSB4 pressure regulator. It must be noted here that most of the pressure drop occurred already at 5 kW power request, where pressure was reduced 0.17 bar to 8.6 barg. Two parallel pressure regulators will be used with the 100-kW fuel cell system to ensure sufficient flow and hydrogen supply pressure at maximum output power.

Air flow through air supply line reached maximum of approx. 2300 slpm measured with Bosch HFM 5 automotive airflow sensor. This is slightly more than specified 2050 Nl/min maximum flow rate for MS30 cathode inlet. However, positioning the airflow sensor and the pressure in the supply line can affect greatly to the accuracy of the sensor. Calibration in the line is thus recommended, if this sensor reading is used for example to drive any system controls. However, in this project these numbers are sufficient as Powercell fuel cell systems control their own air feed. In addition, pressure sensor at air inlet line monitors, if there is any disturbance in the air feed.

During test runs, power electronics control operated smoothly together with the fuel cell system controls. The fuel cell system output power started changing within a second from changing of power request. Depending on the power request change, reaching new output power took 10 – 50 seconds, as the MS30 increased current request gradually and voltage adjusted to the new setting. Also otherwise, CAN bus communication between AVL and fuel cell system functioned without issues.

3.1.3 Cooler performance

The cooling systems of the stack and components were tested while running the Powercell MS30 system up to 22 kW output power. Power output and measured coolant temperature as function of time are presented in Figure 5. Ambient temperature during tests was relatively low: about 9 °C, so the Hydac cooler fans were set to run at 700 rpm, which is about half of the maximum speed. Also, the component cooler fan run at 50 % speed setting.

In the tests, the stack cooling pump run at maximum speed, that results to a coolant flow of 150 lpm according to the specifications. The flow to the Hydac cooler was limited with the proportional valve set to 30 %. In theory, this should result to about 30 % of the flow coming from the pump to be recirculated directly back to the heat exchanger instead of going through the cooler. However, the flows are affected by pressure drops in the tubes, and the flow distribution can differ from the theoretical.

At the maximum 22 kW MS30 output power, the temperature of the primary coolant coming from the fuel cell stack was at 70 °C, while in the stack inlet it was 22.2 °C. The secondary coolant temperature at the heat exchanger inlet was 20.6 °C, while at the outlet temperature was 22.0 °C. Calculated with the 150 lpm glycol/water flow, the cooling power was thus approximately 11 kW. Clearly big share of the heat was dissipated through the fuel cell exhaust.

The cooler specific heat dissipation was above the rated 4.7 kW/K, at 6.1 kW/K. The numbers are within uncertainty limits, as the temperature difference in the heat exchanger inlet and outlet was small. Based on these results and cooler specifications, the cooler can provide the rated heat dissipation of 140 kW in the stack cooling system.

The component cooling had no issues at constant 22 kW fuel cell output power. The coolant temperature from fuel cell outlet settled to about 19.2 °C and coolant temperature after cooler entering the fuel cell was 14.9 °C. The coolant pump was running at 50 % setpoint at 2300 rpm, which would produce 35 – 55 lpm coolant flow depending on pressure. The maximum flow of the pump is 75 lpm. However, the coolant flow is restricted by MS30 that has a maximum component coolant flow of 13 lpm. Thus, the heat dissipation power was about 3 kW. Based on these results and the rating of Ekocoil cooler, the cooling power of the BoP cooling system is anticipated to be adequate for the 100-kW fuel cell system.

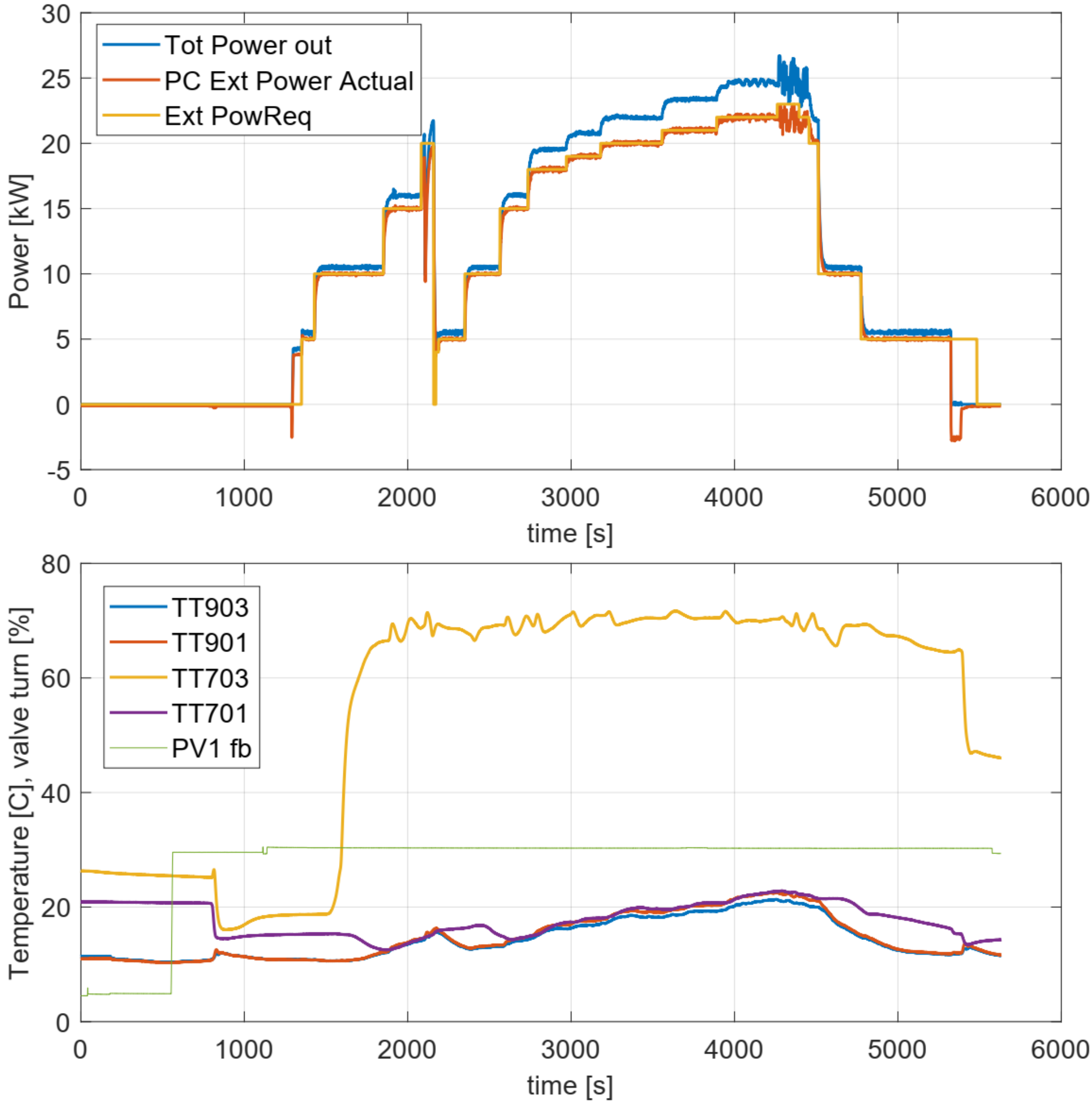

Figure 5. Fuel cell system test power and coolant temperature evolution. The graph above shows the development of system power with time. The lower graph shows the development of coolant temperatures in the stack cooling loops. Once the fuel cell system had reached its operational temperature at 70 °C, the fuel cell coolant outlet temperature TT703 remains stable. The fuel cell coolant inlet temperature TT701 increases slightly together with the secondary coolant temperatures as the fuel cell output power increases.

3.1.4 Safety systems

Functioning of Climate container safety systems was tested with and without the fuel cell system operating. The safety automation proved to function well and sometimes even too sensitively.

In Lynx software, two emergency stops exist by default for two different safety breach severities. The emergency stops are named ‘Soft stop’ and ‘Hard stop’. User can define which system states result in these emergency stops by setting limits for measured parameters. In addition, the actions the automation takes in both emergency stops can be modified.

The Lynx emergency stops were tested by setting software limits so, that normal test operation causes a limit breach. Soft stop functioned as configured setting the fuel cell power request to zero, closed hydrogen supply valve, and changed the fuel cell system status request to Standby as was supposed. Hard stop resulted in turning of the fuel cell system immediately, by turning off the hydrogen supply valve, setting fuel cell system status to Off/Emergency shutdown, and cutting off a 24 V safety loop for the fuel cell system. MS30 enters an emergency shutdown when the safety loop is cut off even if it does not receive Emergency shutdown status request by CAN bus.

The physical emergency shutdown buttons outside the container and in the technical space of the container were also tested. The buttons cut off electric power from the container, and the power is recovered when the emergency shutdown is reset.

The gas monitoring system functioning was confirmed by following the oxygen and hydrogen concentrations during testing and with calibration. The automation was programmed not to allow fuel supply valve to open, if there was more than 4 % oxygen in the container space. The automation was also programmed to initiate a Soft stop if the container oxygen level increased over 4 % during testing.

3.2 Micro GC test

A test run was done with Powercell MS30 with Mirco GC monitoring in the exhaust line. The fuel cell system was operated at 10 kW output power for 20 minutes and the exhaust gas was collected from exhaust line after the outlet from the fuel cell system.

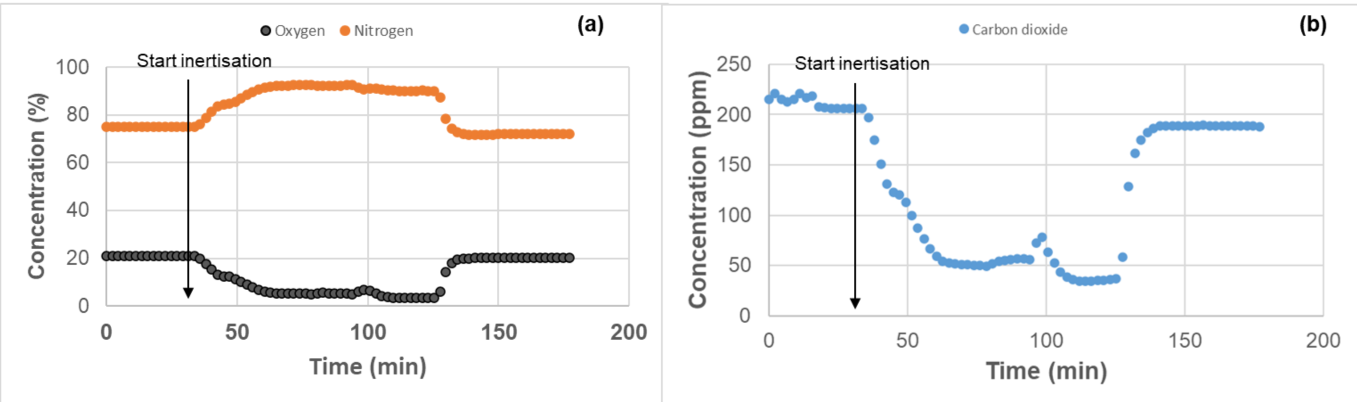

Figure 6. (a) Oxygen, nitrogen and (b) carbon dioxide concentrations of the fuel cell exhaust line

Figure 6 shows the concentration profile of O_2, N_2, and CO_2 from the fuel cell exhaust line in the container. The Micro GC measurement started at 14:51 before the container was closed for testing. Inertisation began around minute 30 in Figure 6, and was complete at 50 min. A decrease in O_2 and CO_2 concentrations during inertisation was realised. At 60 minutes, 10 minutes after inertisation was completed, Micro GC measured 5.2% oxygen. The strong correlation with container oxygen concentration occurred because the sampling line was connected to the container air space through a problematic rotameter in the line. The rotameter was fixed, which solved the issue.

The Micro GC monitoring operated and could measure the changing gas composition in the exhaust line. Before the 100 min tick in Figure 6, the fuel cell system was running and small increase in the oxygen and CO_2 concentrations can be seen, as air is blown through the cathode to the exhaust line.

When testing the 1st and 2nd generation impurity tolerant fuel cell systems, the Micro GC measurement is done mostly from anode line. A buffer tank with check valves opening during purging will be prepared to collect the sample gas for analysis. Micro GC sampling is done from the buffer tank between the purges.

3.3 MFC tests

The impurity mass flow controllers were tested by feeding nitrogen from the impurity line 1, and nitrogen with 1060 ppm carbon monoxide from the impurity line 2 to the hydrogen supply line. The impurities feeds were tested both separately and simultaneously.

During the MFC tests hydrogen was not supplied to the fuel supply line, and the outlet was vented to ambient air above the container. The gas supply pressures upstream of the MFCs were adjusted with regulators to 20 barg that is the rated input pressure of the MFCs.

When tested separately, MFC FT207 in impurity line 2, the controller operated in its rated flow range. The flow measurement was limited to 80 % of the controller range, up to 47.6 slpm. In impurity line 1, MFC FT208 control range was linear at full range. The measurement range was linear up to 80 % of the control range; up to 95.3 slpm.

Cause of the limited measurement range was found to be the AVL analog input resistive load. The Bronkhorst mass flow controllers are specified for load resistance maximum of 375 Ohms, while the AVL resistive load is 500 Ohms. Good calibration of the MFCs ensures the accuracy of the mass flow measurement for the available part of the measurement range. In the project, the maximum range is unlikely required, so using 80% of the range is acceptable.

The MFCs were tested together by flowing gas through both to the hydrogen supply line at various speeds simultaneously. Simultaneous operation had no effect on the flow controllability in the MFCs. Moreover, increase of upstream pressure over 7 bars had no effect on the maximum flow rates.

4. Conclusions and future work

Overall, Climate container proved to be befitting for the upcoming performance validation work in Task 2.1. The required subsystems are operating and allow testing a 100-kW fuel cell system with impurities fed to the hydrogen supply. The buffer volume for anode exhaust gas monitoring with Micro GC is still needed.

The container inertisation allows safe testing of a hydrogen fuelled systems in the container. The experimental safety is ensured by a HAZOP-study which was conducted for the setup as well as experimental testing of all safety procedures.

The cooling systems, and air and fuel supply systems were tested, and they proved sufficient for next tasks in the project. A more powerful high voltage supply is required for the 100-kW fuel cell system and this is going to be purchased. Otherwise, the electric systems are suitable for the next fuel cell systems to be tested.

Fuel cell system communication operated smoothly. The CAN bus messaging in the 1st generation impurity tolerant system has the same core configuration as in the MS30. In addition, part of the CAN frame IDs used to transfer the same information. Therefore, the MS30 was very suitable for testing the Climate Container operation. The work done with MS30 CAN bus makes CAN bus configuration in the next task easier.

Impurity mixing was tested, though without mixing with hydrogen. The mixing concentration can be varied depending on requirement and a fuel cell output power. For long term testing with varying output power, the impurity mass flow controllers should be automated to follow the fuel cell hydrogen consumption to provide constant impurity concentration in the supply. Gas cylinder bundles are needed to house the impurity gases in long term testing in particular, if 5 % of impurity concentration is required.

The Micro GC gas monitoring operated well in the container and there was no discontinuity in the concentration results. Isolation of the sampled exhaust line from the container nitrogen needs to be confirmed in the next fuel cell systems, before monitoring exhaust gases during system operation.

For the task 2.3, preliminary preparations of another fuel cell test setup at VTT build in Maranda[2] project were started and are continued during next months.

5. REFERENCES

[1] "CLEANER - Clean heat and Power from Hydrogen." Accessed: May 01, 2025. [Online]. Available: https://www.cleaner-h2project.eu/
[2] "MARANDA." Accessed: May 01, 2025. [Online]. Available: https://projectsites.vtt.fi/sites/maranda/
[3] "MetroHyVe 2 - Metrology for Hydrogen Vehicles 2." Accessed: Jun. 24, 2025. [Online]. Available: https://www.sintef.no/projectweb/metrohyve-2/

6. APPENDIX

Appendix 1. P&I diagram of the Climate container system